THE QUALITY OF ECMWF HUMIDITY ANALYSIS

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Abstract

The quality of various data types used in the ECMWF humidity analysis is assessed using collocation studies. It is shown that radiosondes, satellites and the first-guess estimate of precipitable water content are of comparable quality. In particular the precipitable water content derived from satellite (TIROS-N), presently not used in the analysis, is shown to have a beneficial impact on the humidity analysis. On the other hand, bogus data derived from surface information appears to be of doubtful quality, particularly at low levels, suggesting the need to re-evaluate the algorithms which are presently used.

1. INTRODUCTION

In recent years there has been much emphasis placed on the representation of dynamical processes in the tropics in GCMs because of possible strong coupling between the tropics and middle latitudes.

The humidity variable is particularly important in the tropics, more so than in mid-latitudes, because geostrophic adjustment time scales are much longer in the tropics (the internal Rossby radius of deformation is much greater): the relaxation time for vertical motion and hence humidity and rainfall fields is of the order of three days in the tropics. It is important, therefore to ensure that the humidity data is introduced into the tropics with some care so that the analysis/initialization procedure does not interrupt the dynamical evolution of the tropical atmosphere. The quality of the humidity analysis is thus an important component, particularly in the representation of the tropical atmosphere.

Here we study the performance of the humidity analysis produced by the ECMWF data assimilation system, and, in particular, assess the quality of satellite precipitable water content data and their impact on the humidity analysis. Satellite precipitable water content is presently not used in our analysis procedure but we will show, using collocation studies, that it is of comparable quality to that derived from radiosondes and the first guess. Furthermore it is shown to have a beneficial impact on the analysis.

2. ECMWF HUMIDITY ANALYSIS SCHEME

The ECMWF analysis is performed in two stages:

(i) MASS and WIND analysis using a 3-dimensional multivariate optimum interpolation scheme.

(ii) HUMIDITY analysis using a 2-dimensional correction scheme.

Here the currently operational humidity analysis is briefly described: for more detailed information see Lorenc and Tibaldi (1979), and Lönnberg and Shaw (1983).

The humidity analysis variable is the integrated mixing ratio of layers enclosed between successive analysis levels:

$$R_{12} = \int_{p_1}^{p_2} r\,dp$$

where r is the mixing ratio in g/kg, and p_1 and p_2 are standard pressure levels up to 300 mb. Because R_{12} is proportional to precipitable water content, defined as:

$$pwc_{12} = \frac{1}{g}\int_{p_1}^{p_2} r\,dp = \frac{1}{g} R_{12}$$

hereafter we refer to the analysis variable as precipitable water content (pwc).

No humidity analysis is performed above 300 mb; instead R is extrapolated towards a climatological value.

The humidity analysis is based on the assumption that the background field provided by the model forecast is reasonably accurate. This assumption will be tested in Section 3. The prediction error correlation is assumed to have a Gaussian structure with a horizontal correlation scale which varies from 250 km at the surface to 350 km at 300 mb. Estimated values of the prediction error and the estimated observational error ascribed to the various observation types are taken into account when determining the weight given to each observation. The interpolated value in the analysis is the deviation from the background field and so, if no datum disagrees with it, the background field is left unchanged. Thus the present scheme is a one-scan correction scheme in which the weights are statistically determined.

2.1 Humidity data

Three types of observations are available for use in the humidity analysis:

(i) radiosondes (TEMPS)

(ii) surface observations (SYNOPS)

(iii) satellites (SATEMS),

but presently only radiosondes and surface observations are used in the ECMWF humidity analysis.

(i) Radiosondes provide temperature and dew point at standard and significant levels. They are used to estimate the mixing ratio at all levels and the integrated mixing ratio (analysis variable) between standard pressure levels.

(ii) Surface observations provide temperature and dew point, as well as current weather, cloud amounts and types, from which some humidity information can be inferred. Each surface observation is used to provide an estimate of the average relative humidity in four layers, roughly equivalent to the planetary boundary layer, low, medium and high cloud, following the algorithm developed by Chu and Parish (1977) and used at NMC.

(iii) Satellite soundings provide precipitable water content between a reference level and standard pressure levels, but they are not used in the present operational system. Here we will consider the quality of FGGE TIROS-N moisture data produced by NESS using a statistical retrieval method (see Smith and Woolf, 1976).

Fig. 1 indicates the density of data coverage obtained from TIROS-N during FGGE (12 June 00 GMT, 1979). It is clear that they provide extensive spatial and temporal coverage. However they are deficient in resolving the vertical structure. The principle by which moisture information is derived from satellite measured radiances is very similar to that used in temperature retrievals - the same eigenvector regression technique is used to obtain the vertical profile of water vapour mixing ratio, from the radiances measured by those channels which are particularly sensitive to water vapour. Fig. 2 shows the three channels most sensitive to water vapour. As can be seen, they poorly resolve the vertical structure. In addition, cloud contamination even in partly cloudy conditions can be very severe. Perhaps because of these limitations, little effort has been put into an evaluation of satellite derived moisture data or their use in the analysis.

In this study an attempt is made to assess their quality and their impact on the humidity analysis.

3. STATISTICAL EVALUATION OF HUMIDITY ANALYSIS

To assess the quality of any analysis it is important to assess the relative accuracy of both the data and the first guess. Here a statistical evaluation of humidity data together with the first guess is attempted.

The study is based on the "humidity statistics file", which is routinely produced at the end of each analysis cycle and contains departures of the observed values from the first guess, analysed and initialised fields: the departures of (OB-FG), (OB-AN), (OB-IN) are stored at each observation point

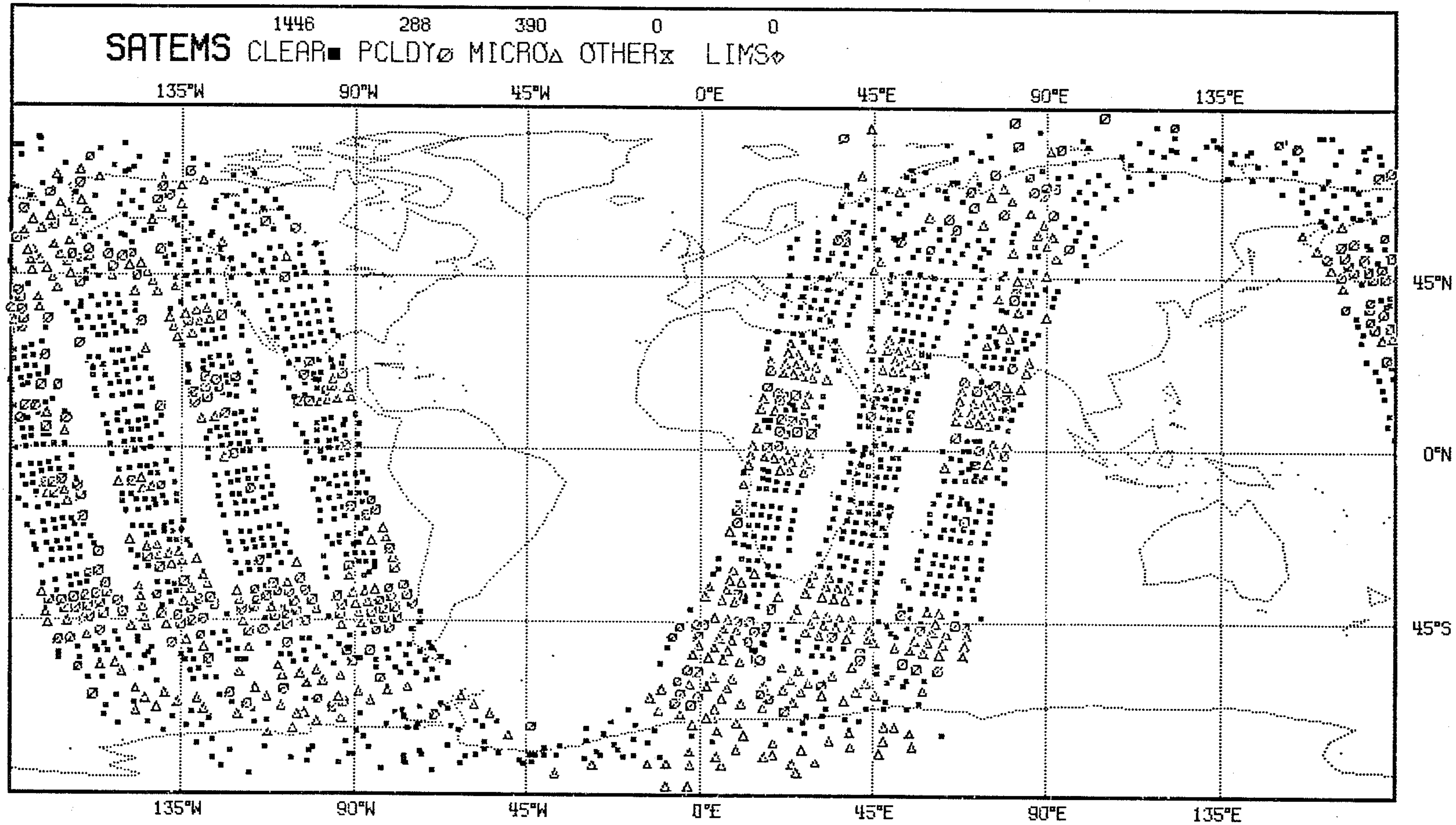

Fig. 1 The coverage of TIROS-N satellite on 12 June 1979, 00GMT (FGGE IIb data).

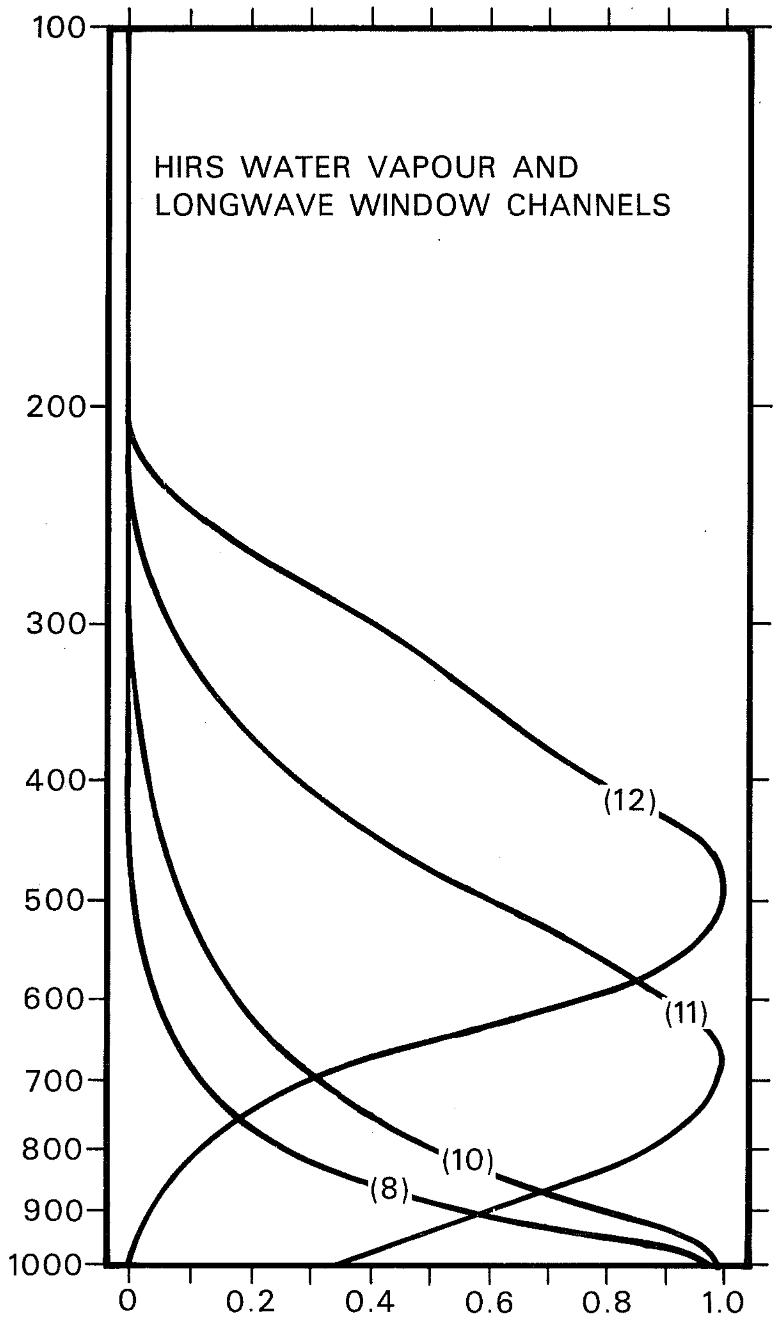

Fig. 2 HIRS water vapour and long wave window channels.

for the analyzed humidity variable, the precipitable water content. Using this information a statistical evaluation of the humidity data is performed by means of collocation studies between

(a) satellite data and radiosondes

(b) surface data and radiosondes.

In addition the quality of the first guess is assessed relative to the observations.

3.1 Quality of the data

The collocation procedure is the following: from an ensemble of humidity statistics files, the variance of the difference between the departures of each observation type from the first guess is evaluated. For example for satellite and radiosonde data

$$\mathrm{Var}[(\mathrm{SAT}-\mathrm{FG}_1) - (\mathrm{RAD}-\mathrm{FG}_2)]$$

$$= E^2_{SAT} + E^2_{RAD} + E^2_{FG_1} + E^2_{FG_2} - 2\mathrm{Cor}(E_{FG_1}, E_{FG_2}) \qquad (1)$$

where

E_{SAT} = satellite observational error

E_{RAD} = radiosonde observational error

$E_{FG_1} = E_{FG_2} = E_{FG}$ = prediction error

In the limiting case where the collocation distance is small compared to the correlation scale of the field, (1) becomes

$$\mathrm{Var}[(\mathrm{SAT}-\mathrm{FG}_1) - (\mathrm{RAD}-\mathrm{FG}_2)] \simeq E^2_{SAT} + E^2_{RAD} \qquad (2)$$

That is, the variance of the difference of the two departures is equal to the sum of the squares of the observational errors.

For the purpose of this study the collocation distance has been chosen to be 100 km which is small compared to the typical humidity correlation scale, estimated to be 300 km (Van Maanen, 1981) and so our assumption leading to (2) is expected to hold. The time-window of the collocation is ±3 hours and the period for the collocation was chosen to be from 11 June 12 GMT to 14 June 12 GMT, 1979.

The results are presented for two different areas: the northern hemisphere (90°N-20°N) and the tropical belt (20°N-20°S).

(a) Collocation of satellite with radiosondes

In an attempt to evaluate the quality of TIROS-N pwc data during FGGE, a collocation study with radiosonde data has been performed. However, before discussing the results it is important to remember that moisture is not a very conservative atmospheric parameter, and is highly variable in space and time. Thus it will always be difficult to devise a reasonable method of verifying satellite data. Instantaneous spot profiles obtained regularly from radiosondes are not ideal for this purpose. However because radiosondes provide the most reliable moisture data against which satellite data can be compared, we collocated TIROS-N pwc data with radiosondes for the 4 day period during FGGE. Because satellite derived pwc only gives integrated measures, these were interpolated to layers between standard pressure levels using the first guess.

Fig. 3 shows the results of the collocation over the northern hemisphere and the tropics for the pwc. The bias is generally small, but in the tropics the bias is significant in the 700-500 mb layers, where the satellites show a

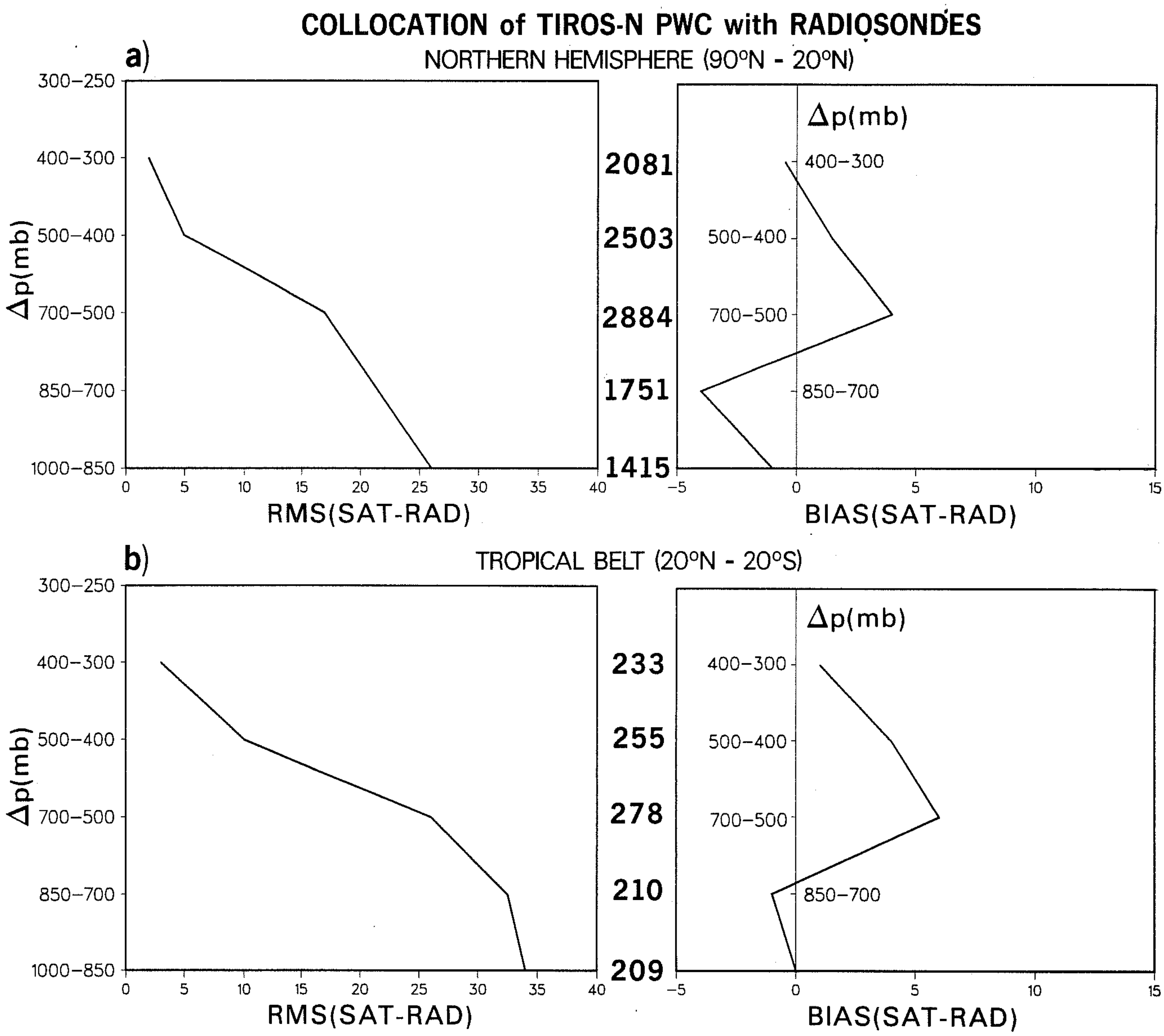

Fig. 3 Root mean square and bias statistics of the difference between satellite and radiosonde for the analysis variable of precipitable water content (pwc) over a) Northern Hemisphere, b) tropical belt. Data values are indicated by N for each level.

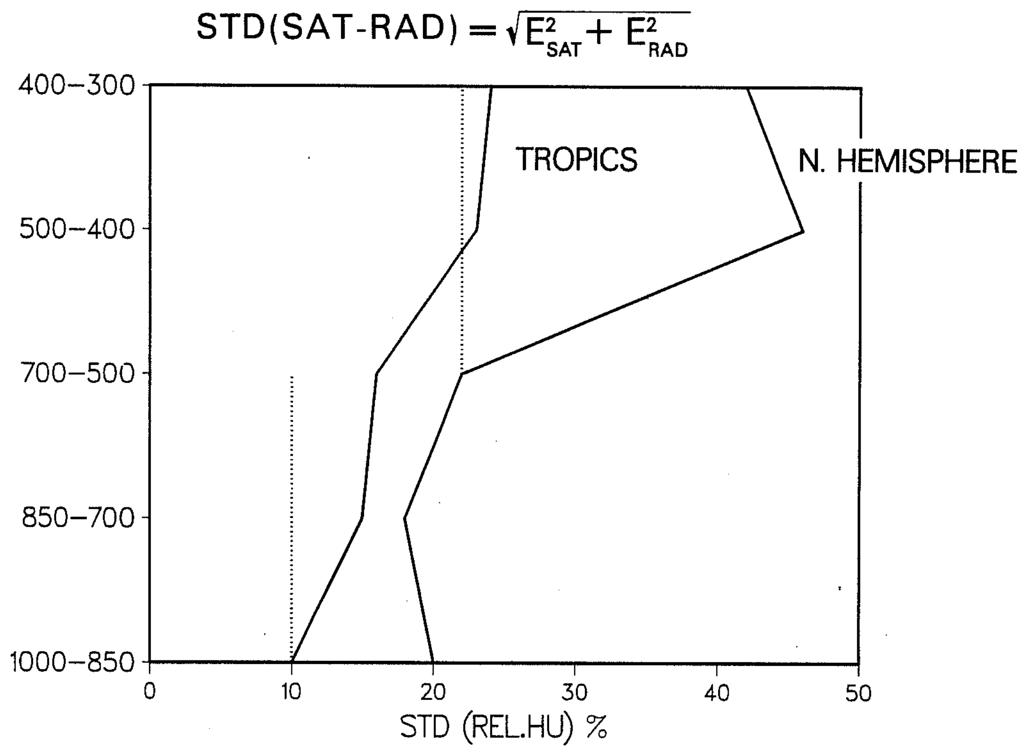

Fig. 4 Standard deviation of the difference between satellite and radiosonde in relative humidity (continuous line) and the radiosonde observational error (dashed line).

tendency to overestimate the moisture. The variance of the differences follows closely the climatological variance, decreasing sharply with height. Because the observational error ascribed to radiosondes by the manufacturers is given in terms of relative humidity, the root mean square error (rmse) curves of Fig. 3 have been normalised so as to obtain the error in relative humidity. These are presented in Fig. 4, which gives the total error after normalization with the saturation mixing ratio evaluated at the mean temperature of the layer:

$$\mathrm{STD(REL\ HUM)} = \sqrt{E_{SAT}^2 + E_{RAD}^2}$$

where according to the manufacturer E_{RAD} is 10% for normal condition or 20% for dry and very cold condition.

From Fig. 4 it is clear that the satellite error is at least comparable to the radiosonde error. In the tropics the satellite error varies between 15% and 20% . However in the Northern Hemisphere it varies from 15% in the lower troposphere to 35% in the upper troposphere, where it is difficult to sample moisture because of very dry and cold conditions.

Generally we can conclude that the satellite data are of comparable quality to radiosonde data. They are able to measure the total moisture in a layer without a large bias. It should be noted, however, that in abnormal situations the bias may be larger than we have indicated, because the regression coefficients used are based on the statistics of the previous week and so do not contain local information (see Gruber and Watkins, 1981).

(b) Collocation of SYNOPS with radiosondes

Collocation of SYNOPS with radiosondes shows that the humidity information deduced from SYNOP reports (dewpoint temperature, actual weather and cloud cover) according to the Chu and Parish (1977) algorithm grossly overestimates the moisture. Fig. 5 shows the results for the northern hemisphere and the tropics. It is clear that the SYNOP data are wetter than the radiosonde data, particularly in the tropics and at the surface. This bias mainly results from the misuse of current weather reports and cloud cover observations, particularly in partly cloudy conditions. It is, in fact, very difficult to provide any reliable estimate of moisture from the current weather reports and from cloud cover estimates, particularly in cases when the cloud cover is low. On this basis, an alternative use of SYNOP data is being developed which uses surface measurements of temperature, pressure and dew point, (the most useful information provided by SYNOPS) together with cloud-cover estimates but only when they are greater than 7 oktas. It is, in fact, thought that the cloud information is useful for the almost or completely overcast situation since these are precisely the cases in which the TIROS-N infra-red sensor is incapable of providing humidity data. Preliminary tests of this new formulation have proved encouraging (see Pasch and Illari 1985).

3.2 Quality of the first guess

We may regard the GCM as a measuring instrument providing observations of the field which we call the first guess. It is natural, therefore, to enquire into the accuracy of the first guess. Here the first guess is provided by the 6-hour forecast of the ECMWF T63 spectral model and it is compared to radiosondes and satellite data.

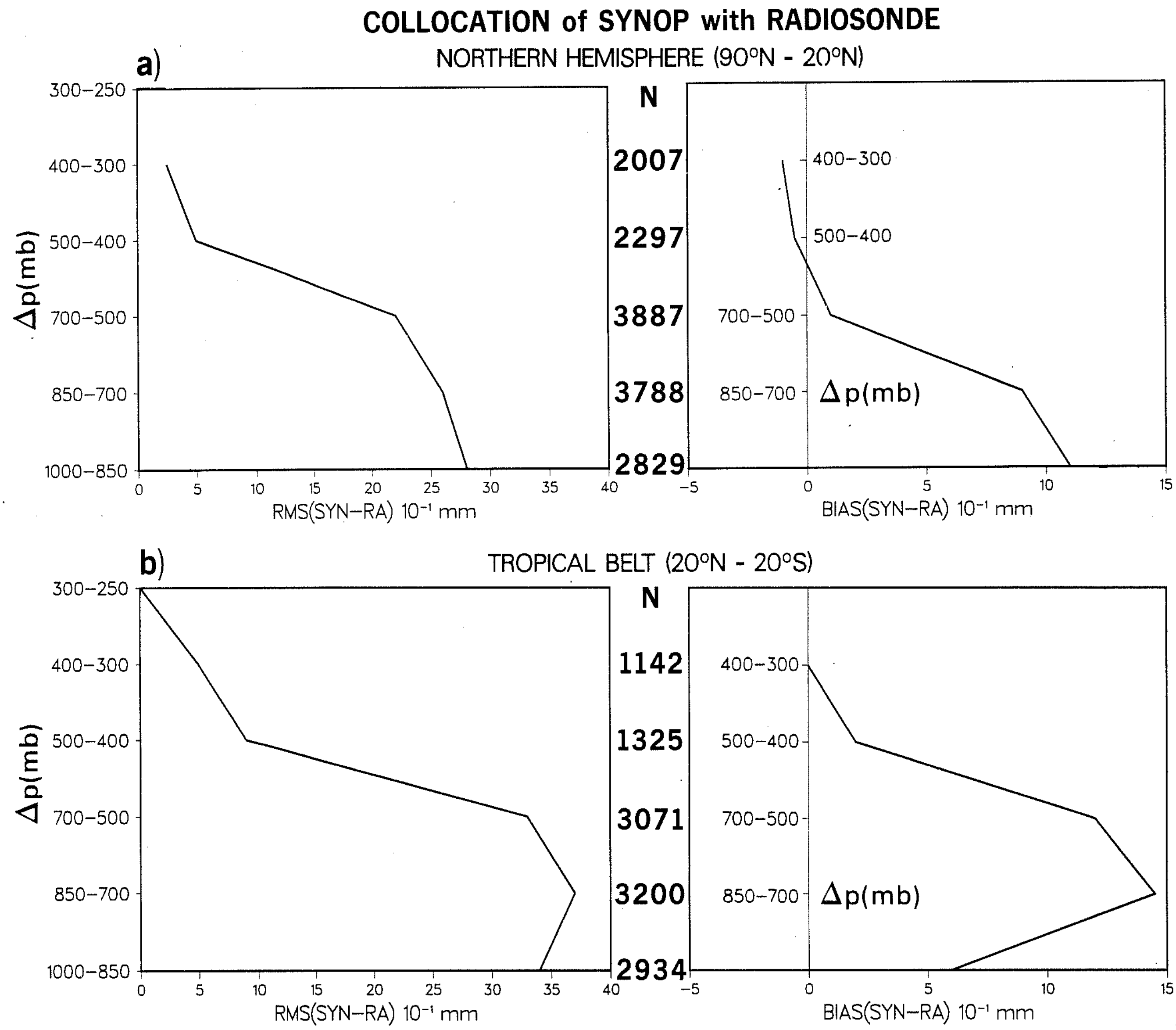

Fig. 5 Root mean square and bias statistics of the difference between SYNOPs and radiosondes for the analysis variable of precipitable water content (pwc) over a) Northern Hemisphere b) tropical belt. Data values are indicated by N.

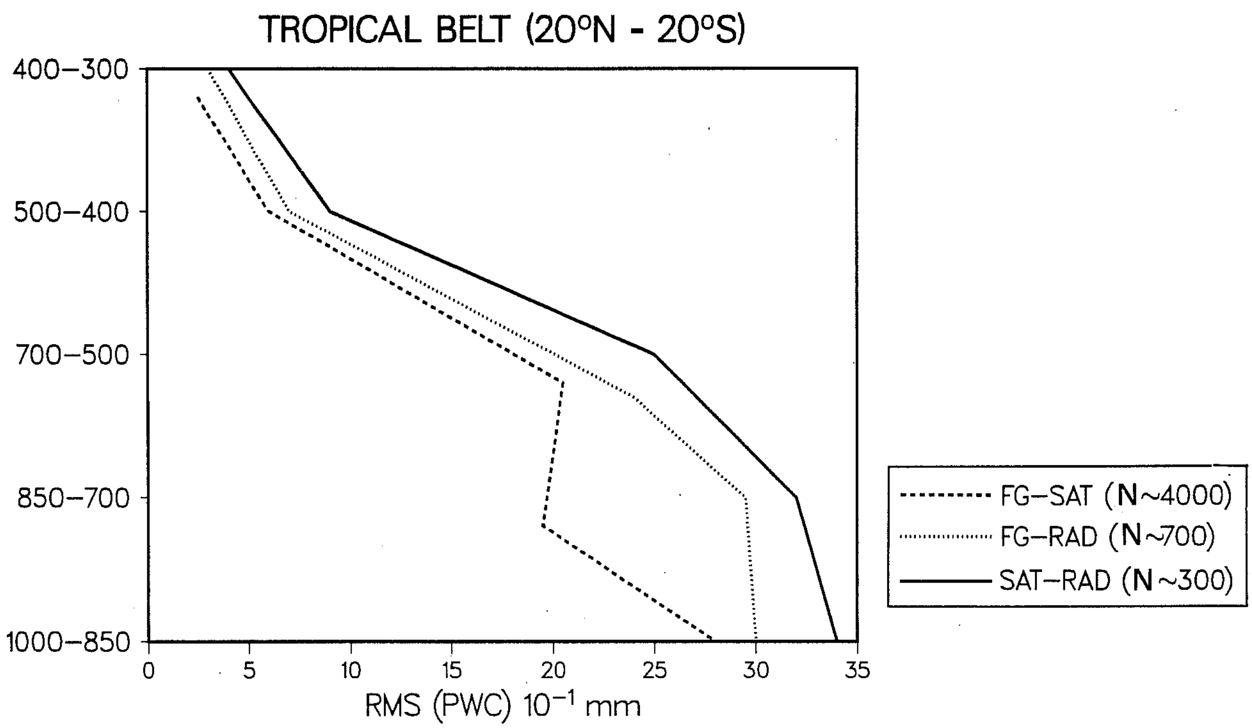

Fig. 6 Root mean square statistics for the difference between a) first guess and satellite (dashed line) c) satellite and radiosonde (continuous line) for the analysis variable of precipitable water content (pwc). Data values are indicated by N.

Using the humidity statistics file for the same 4-day period in June 1979, we calculate the variance of the difference of the observations from the first guess:

$$\text{Var(OB-FG)} \simeq E_{OB}^2 + E_{FG}^2$$

This says that the variance of the difference is approximately equal to the sum of the squares of observational error (E_{OB}) and first guess error (E_{FG}), where we have assumed that observational errors and first-guess errors are uncorrelated.

Fig. 6 shows the rmse of the difference in pwc over the tropics between first-guess and radiosonde, first guess and satellite and for comparison satellites and radiosondes. It is clear that the first guess and the data are of comparable accuracy. Furthermore, the rmse curves follow closely the climatological variance sharply decreasing with height. They explain 60% to 70% of the climatological variance. This highlights the difficulty of our observing system in sampling a field such as moisture which is highly variable both in space and time. However it is worth emphasizing that there appears to be little difference in the quality of satellites, radiosondes and first-guess.

4. DATA ASSIMILATION EXPERIMENTS

Sensitivity studies have been performed to assess the quality of the humidity analysis and how it is affected by the first guess field and observation types. Here we will describe two 3½ day data assimilation experiments from 8 June 00 GMT to 11 June 12 GMT, 1979 which have been carried out to evaluate the impact of changes in the physical parameterization of the first guess and the impact of use of satellite data.

4.1 Impact of changes in the first-guess

Here we assess the impact of changes in the first guess, due to the implementation of a new physical parameterization of shallow convection and modified Kuo scheme for deep convection. These changes became operational in May 1985 (for a fuller discussion see Tiedtke and Slingo 1985). We will refer to this version of the physical parameterization as the "new physics".

Two experiments were run, one with the old version of the physics, the "old physics" experiment, and one with the new version of the physics, the "new physics" experiment.

The impact of the "new physics" on the humidity field is large and tends to correct well documented systematic errors associated with the "old physics". Comparison with climatology had shown that the moisture analysis was too wet at the surface and too dry at 850 mb (Heckley, 1985).

Fig. 7 shows the relative humidity difference between assimilation experiments with "old physics" and with "new physics". The data are the same in each case (satellite data have not been used). It is clear that the "new physics" acts to

(i) dry the surface (Fig. 7a)

(ii) moisten the tropics and subtropics at 850 mb with changes in relative humidity of up to 50%, 60% (Fig. 7b).

A cross-section of mixing ratio along 20°N shows the impact of the "new physics" clearly: the moisture content is reduced in the boundary layer and is increased above (Fig. 8), in the sense to correct for systematic errors.

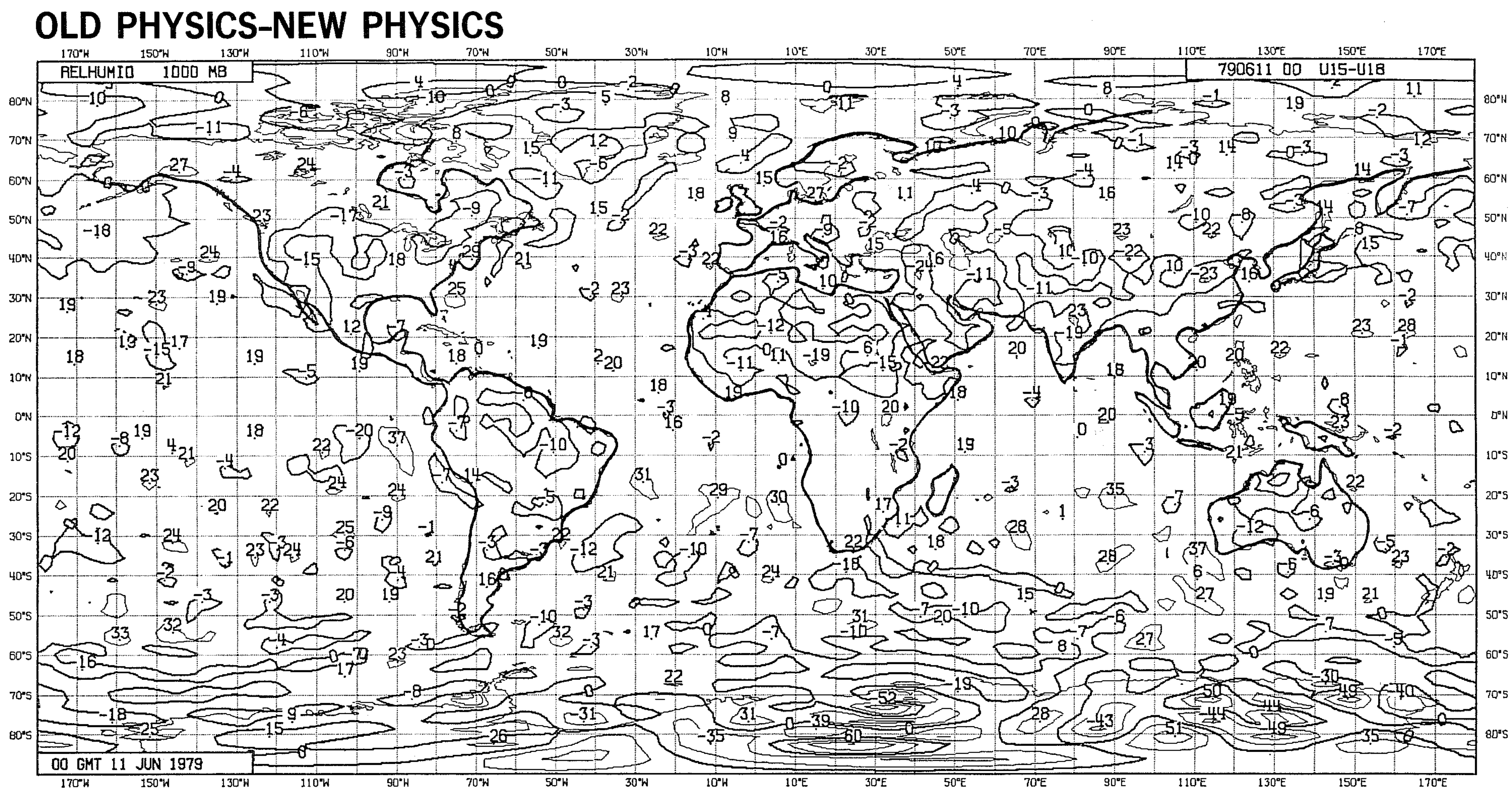

Fig. 7 a) The relative humidity difference field (%) between "old physics" experiment and "new physics" experiment at the 1000 mb surface

OLD PHYSICS-NEW PHYSICS

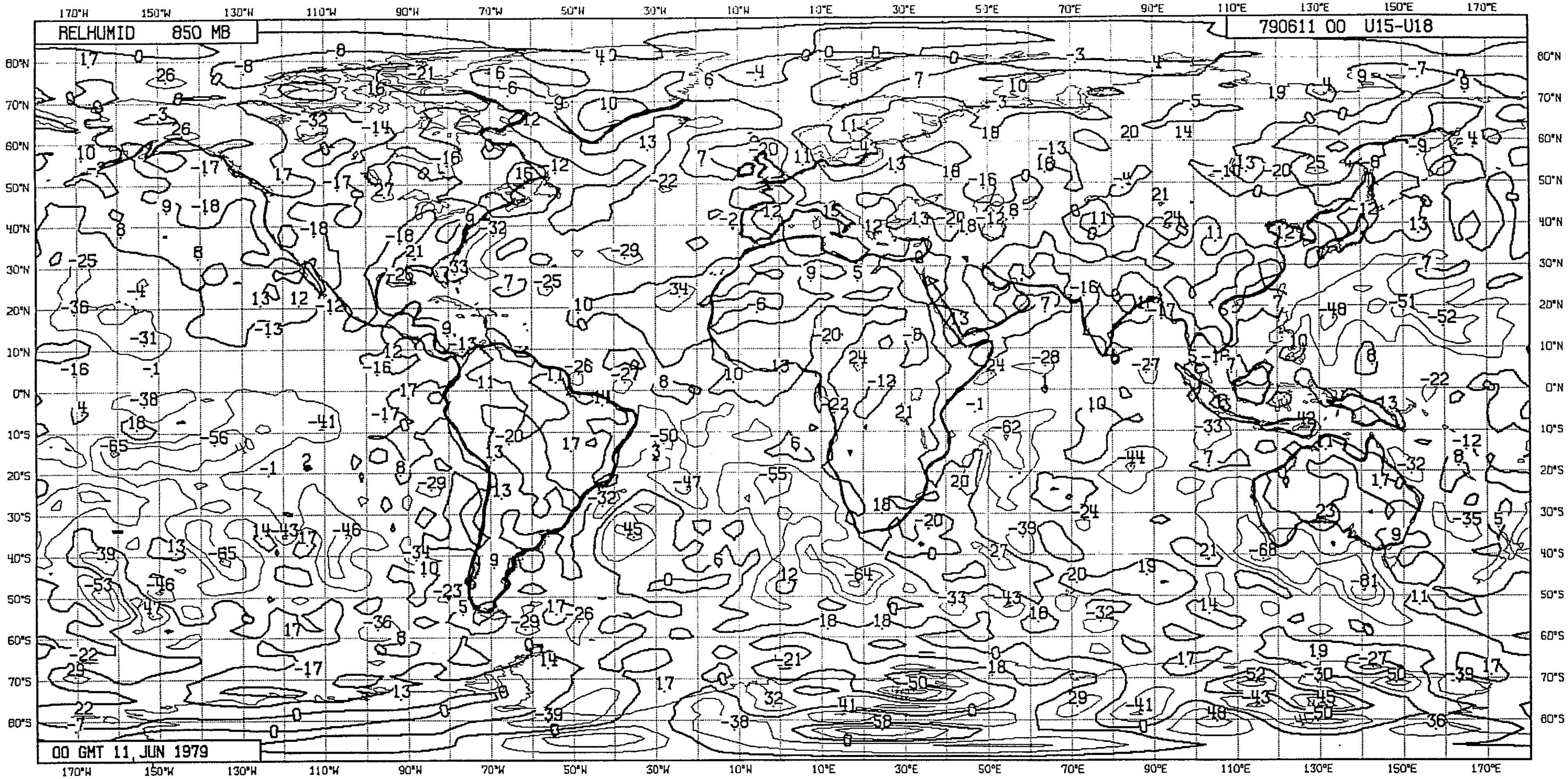

Fig. 7 b) As in Fig. 7a but for the 850 mb surface.

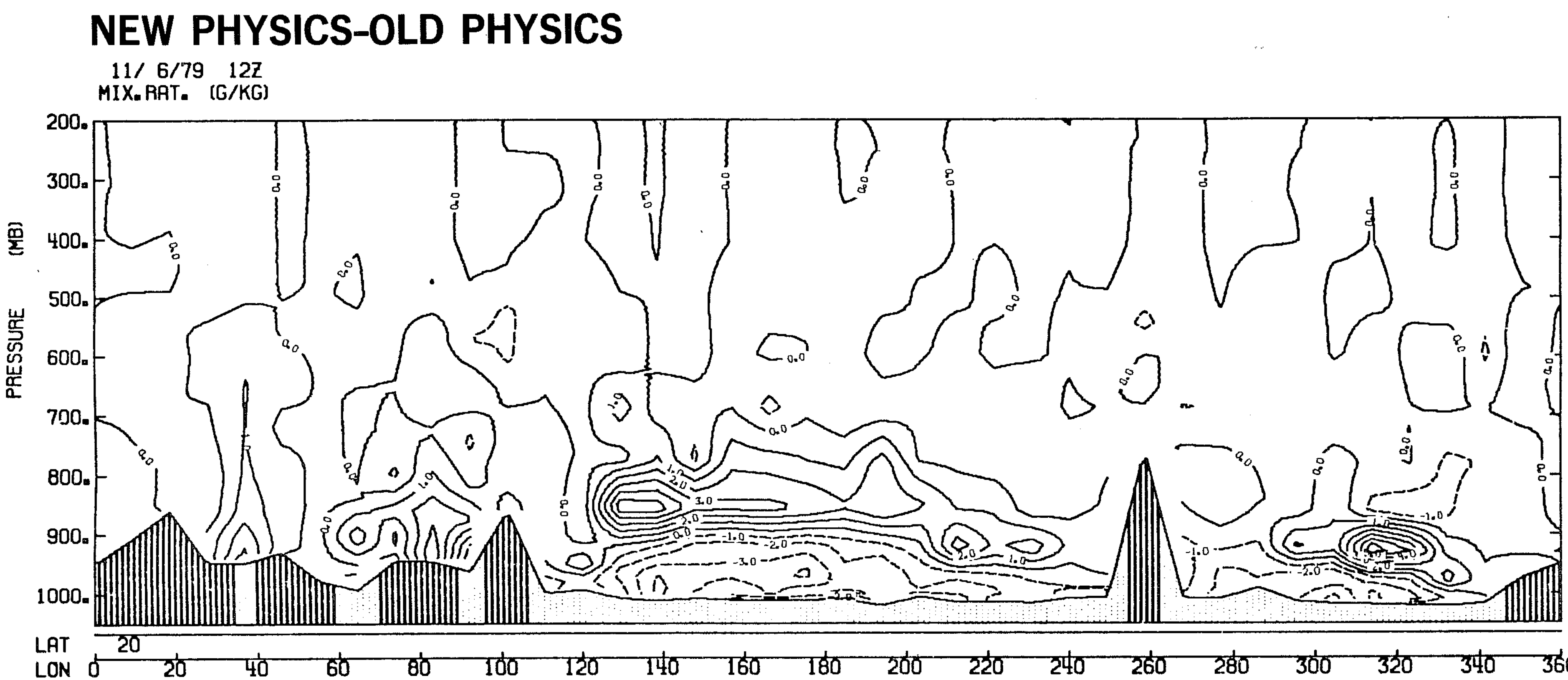

Fig. 8 Zonal cross-section of mixing ratio along 20°N showing the difference between the "new physics" and "old physics".

4.2 Impact of satellite data (TIROS-N pwc)

To assess the impact of satellite data on the humidity analysis, a data assimilation experiment, including the "new physics" together with satellite pwc data, has been run for the same FGGE period as used in the previous experiment.

Based on the statistical evaluation of satellite data described in Section 3, the observational error ascribed to satellite data has been chosen to be 20% slightly more than the radiosonde error (10%), while prediction error is chosen to be 10% in the extratropics and 15% in the tropics.

The satellite data have quite a large impact on the humidity analysis, affecting mainly data sparse areas over the oceans. At the surface they tend to moisten the oceanic regions (Fig. 9a) with differences in the southern oceans of up to 50%. In the lower troposphere (500 mb) they dry some regions and moisten others (Fig. 9b). However, overall the satellite data tends to moisten the tropics and subtropics by about 20% in relative humidity.

It is, of course, difficult to assess whether these changes improve the description of the moisture field in the assimilation. One way to assess the quality of the humidity analysis is to compare derived quantities which should be highly dependent on moisture. The most obvious choice is the 6-hour forecast of precipitation, but we should only draw tentative conclusions since the vertical motion fields clearly play the most decisive role in determining the rainfall pattern, rather than the relative humidity fields. However, it would be incorrect to view the humidity as a purely passive variable, since the evolving vertical motion field is itself the product of feedback from diabatic processes as well as the dynamics. These diabatic processes can be modified by changes to the humidity variable. Thus we expect changes in the precipitation field to contain a signature reflecting the impact of changes in the humidity analysis.

NO SAT-SAT

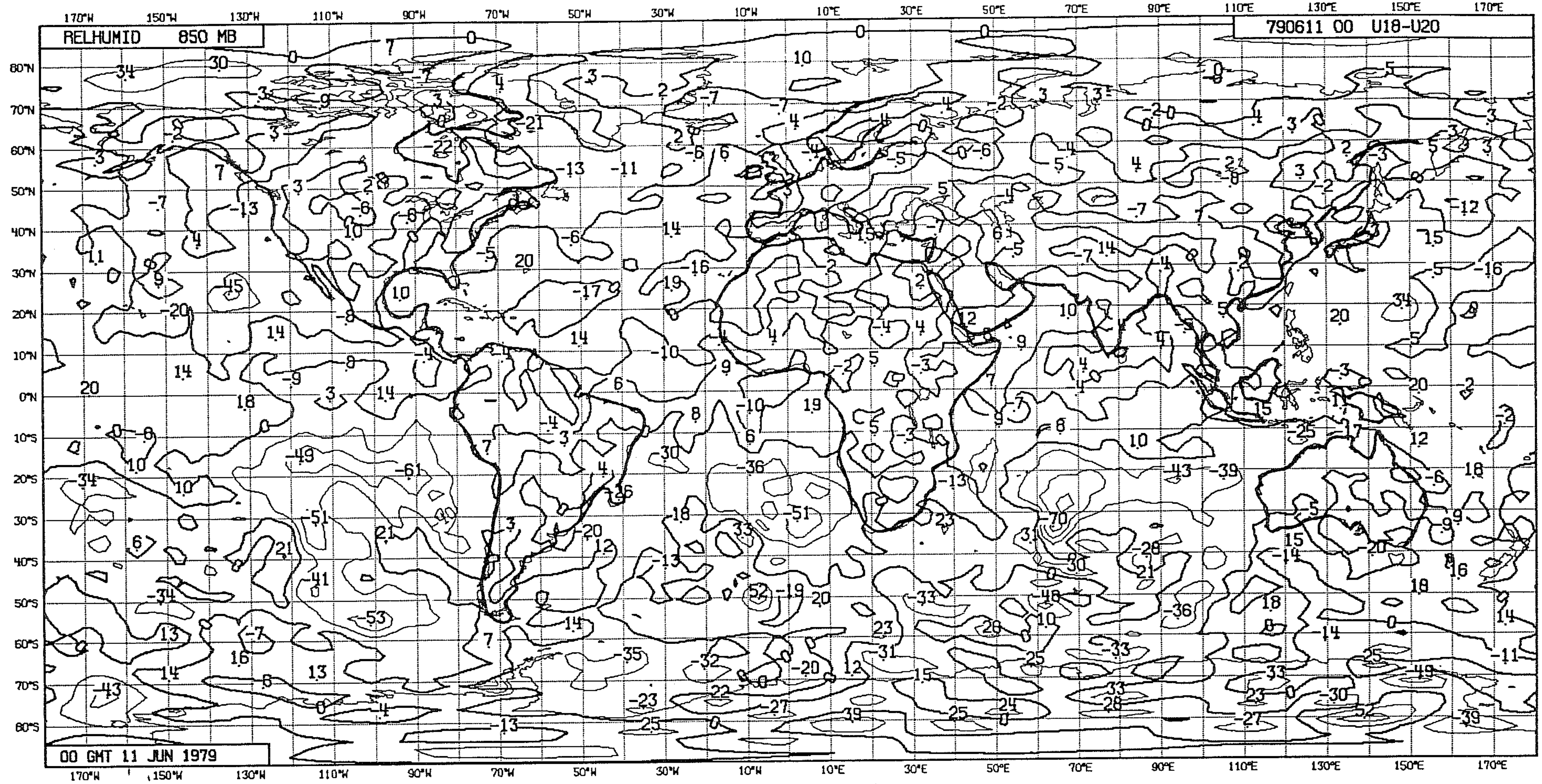

Fig. 9 a) The relative humidity difference field (%) between the "NO SAT" experiment and the "SAT" experiment at 850 mb

NO SAT-SAT

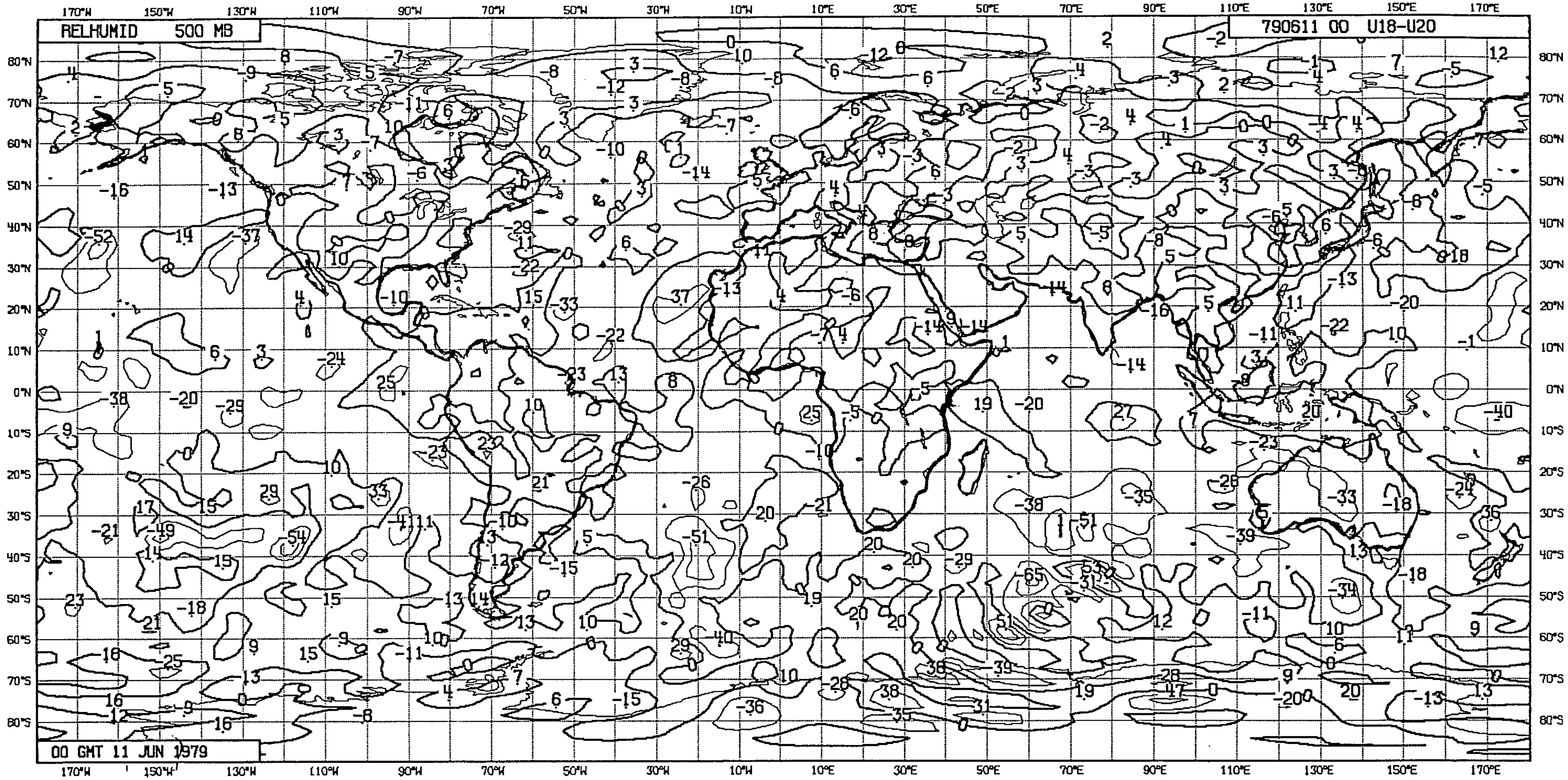

Fig. 9. b) as in a), but for 500 mb.

NO SAT

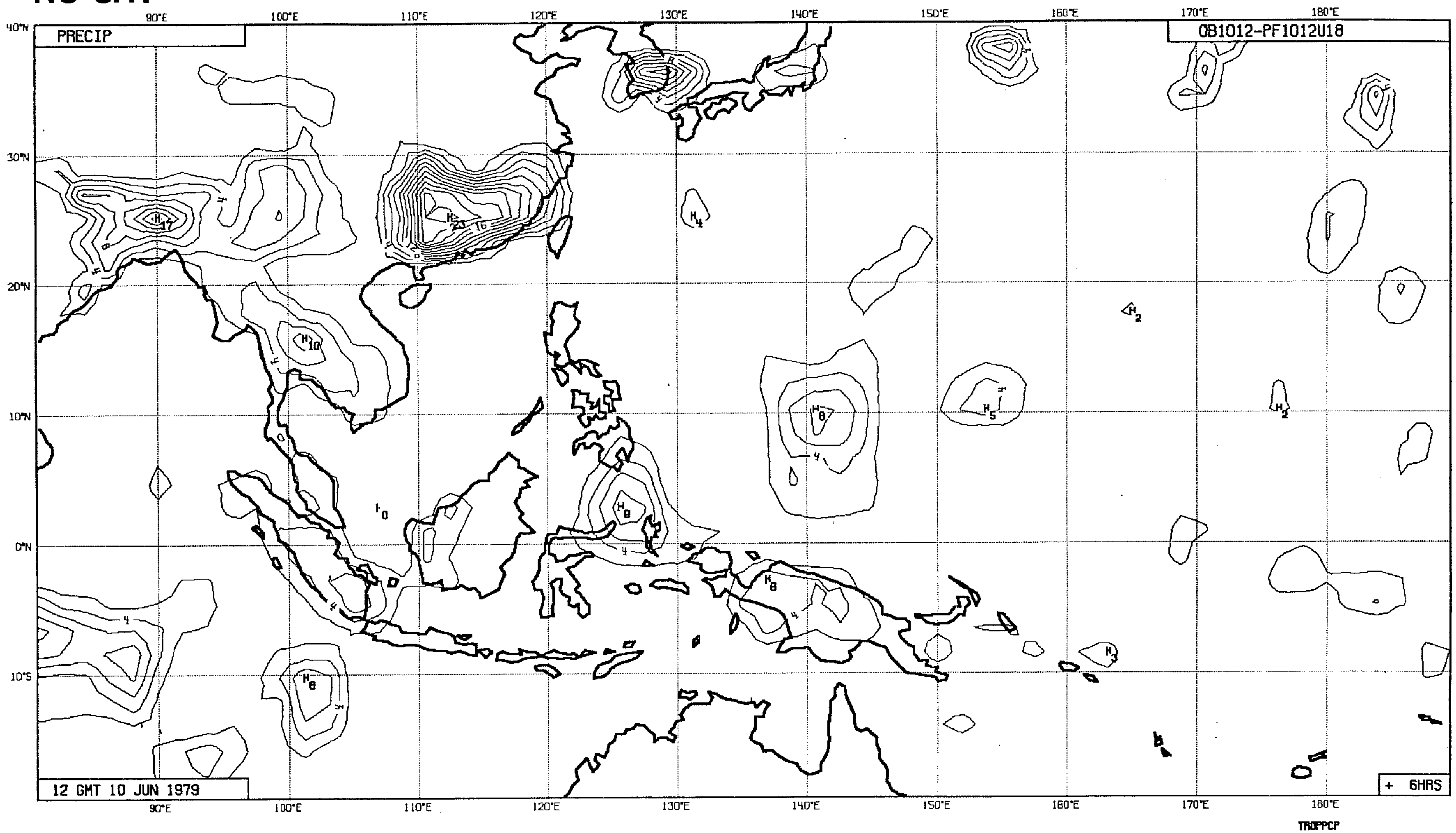

Fig. 10 Accumulated precipitation for the 6-hour period ending 12ZT, 10 June 1979 from the "NO SAT" experiment. Contour interval 2mm.

SAT

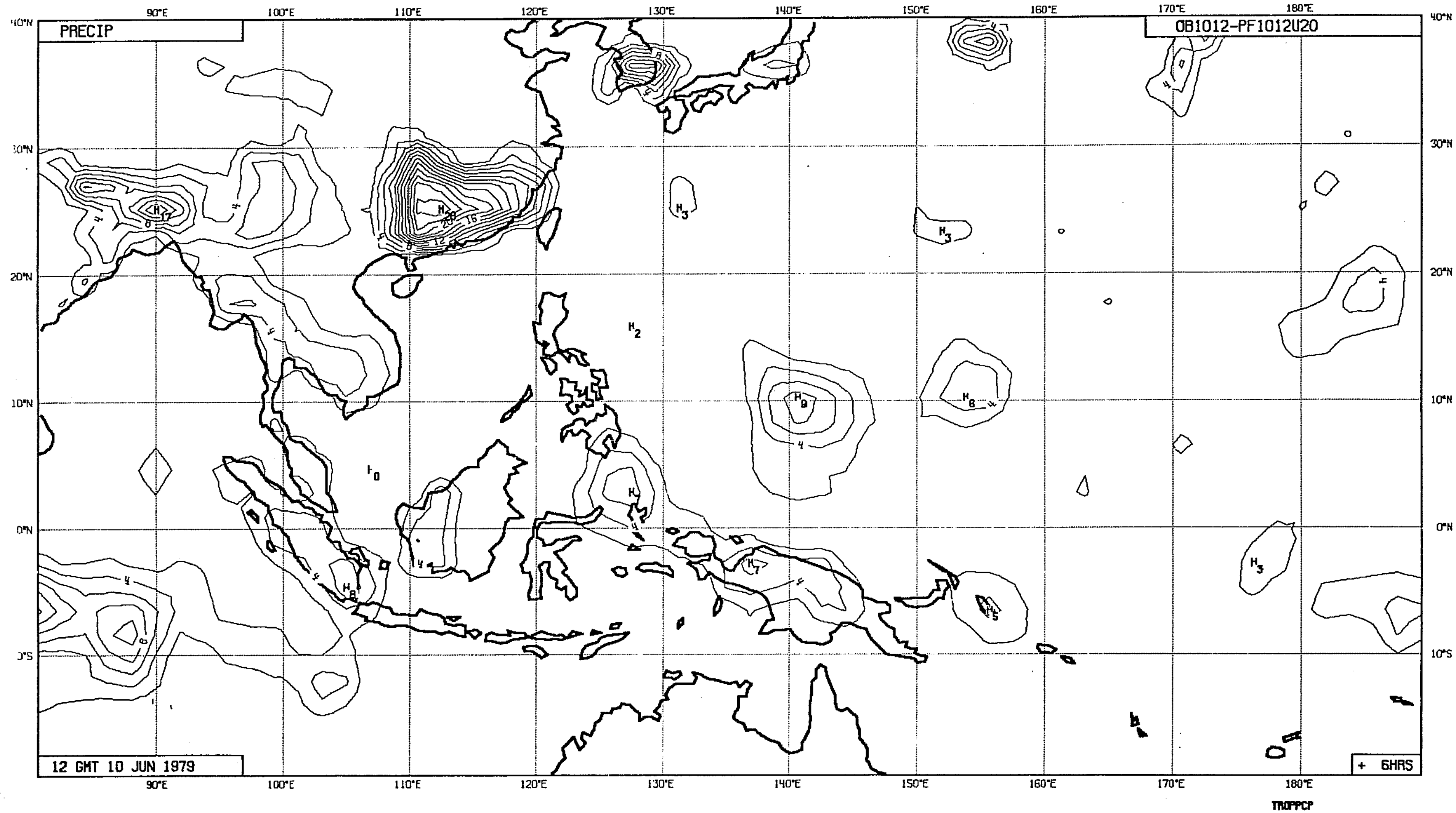

Fig. 11 As in Fig. 10 but for the "SAT" experiment

CONVECTIVE INDEX

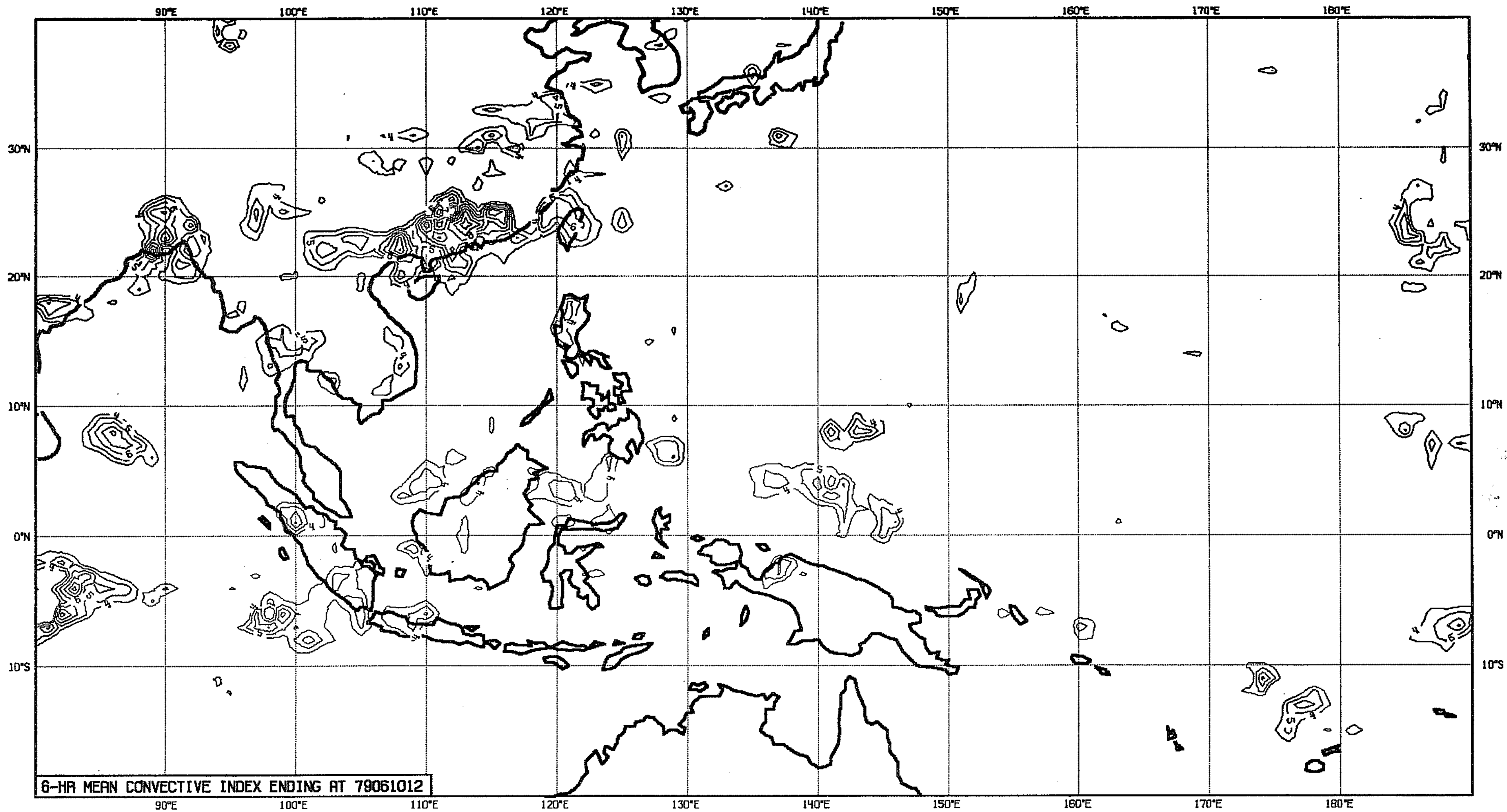

Fig. 12 The field of convective activity index for the 6 hour period ending 12GMT, 10 June 1979 derived by Murakami (1985). More than 4 units implies vigorous convective activity.

Figs. 10 and 11 show the 6 hour precipitation from the experiment without satellites (NO SAT) and the experiment with satellite (SAT). These should be compared with Fig. 12, which shows a satellite derived index of convective activity, for the same period, derived by Murakami (1983), from the infra-red sensor on the GMS satellite. Values of 5° or greater denote very active convection and significant rainfall.

The difference between the rainfall from the NOSAT assimilation (Fig. 10) and the SAT assimilation (Fig. 11), although small, appears to be meaningful when compared to the observed convective activity (Fig. 12). By incorporating the satellite data more realistic rainfall features are obtained in some areas; for example the rainfall over Thailand (15°N, 100°E) has been reduced in agreement with observations, as has the rainfall over Indonesia (5°N, 125°E); the rainfall centred at 10°N, 140°E, as well as the maxima at 10°S, 90°E, have been intensified by incorporating satellite data, in agreement with the observed convective activity.

Although these changes are small, we conclude that the use of satellite data is beneficial and improves our prediction of rainfall.

5. CONCLUSIONS

We conclude by briefly summarising our results:

(i) Satellite precipitable water content data are of reasonable quality (compared to radiosondes) and have a beneficial impact in data assimilation experiments.

(ii) The first guess field has been improved by the new physics and is of comparable quality to the data.

(iii) Surface data are of doubtful quality, particularly at lower levels and low cloud amounts.

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